How Big?

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Power conductors in renewable energy systems range from #18 (0.8 mm^2) through #4/0 (107.2 mm^2), and up to the largest in the range of 300 kcmil (210 mm^2). The task of this column will be to discuss how the ampacity of conductors is determined in a particular installation or situation.

Conductor size in the United States is measured (with no insulation) in AWG, which stands for American Wire Gauge. The larger the AWG number, the smaller the conductor. A bare copper #18 (0.8 mm^2) conductor has a diameter of about 0.04 inches (1 mm) and an area in circular mils of about 1,620. (I didn't make this up. A mil is 1/1,000 of an inch, and a circular mil is an area calculated by the diameter in mils squared.)

Insulation on the conductor will make the overall conductor larger, and the exact size will depend on the type of insulation used. Conductors larger than #1 are numbered #1/0 through #4/0. (These are the same as 0 and 0000 and are pronounced "one aught" and "four aught".) Conductors larger than #4/0 are numbered by their area in thousands of circular mils (kcmil), starting with 250 kcmil (170 mm^2). Here is a table of the commonly used conductors, their diameters, and areas in square inches and circular mils.

Metric wire sizes use the cross-sectional area as their designator. Ideally, European conductor size equivalents should be made based on equivalent rated ampacity, not conductor sizes translated from inches to millimeters. If in doubt, use a metric size that is larger than the AWG equivalent. And make sure that the rated ampacity of the cable meets local codes for your intended application.

How Good Is That Cable?

The current-carrying capability (ampacity) of a conductor is related to how hot the cable insulation is allowed to get. The toughness of the insulation, its flexibility at cold temperatures, and its aging properties under various conditions (UV, oil, water, etc.) are also important parameters in establishing the quality of an insulated conductor.

The International Cable Engineers Association (ICEA) works with the cable manufacturers to develop standards for cable insulation. Their goal is for cables in normal installations to last more than twenty years when operated at the maximum temperature in specific environments that apply to that particular insulation. The ICEA Standards are then transferred to an independent party, Underwriters Laboratory (UL). They develop testing standards that enable independent testing agencies (UL, ETL, and only a few others) to test various cables to ensure that they meet the safety and durability standards.

The tests on a particular cable by a specific manufacturer must be repeated periodically (typically every three months) to ensure that the cable continues to meet the standards. This process of testing and retesting to a standard by an independent agency like UL is the process called "listing." It results in some sort of safety seal—such as the "UL in a circle" mark—being affixed to every product that meets the standard. Without this or a similar mark, there is no way of telling that the cable is safe to use in a particular application. Without continued testing, there is no way to ensure that the cable, as manufactured, continues to meet the standard.

Common Wire Sizes

*Size**	*Diameter in inches***	*Area in inches^2*	*Area in circ mils*	*Area in mm^2*
18	0.040	0.001	1,620	0.823
16	0.051	0.002	2,580	1.309
14	0.064	0.003	4,110	2.082
12	0.081	0.005	6,530	3.308
10	0.102	0.008	10,380	5.261
8	0.128	0.013	16,510	8.367
6	0.184	0.027	26,240	13.299
4	0.232	0.042	41,740	21.147
3	0.260	0.053	52,620	26.670
2	0.292	0.067	66,360	33.624
1	0.332	0.087	83,690	42.406
1/0	0.372	0.109	105,600	53.482
2/0	0.418	0.137	133,100	67.433
3/0	0.470	0.173	167,800	85.014
4/0	0.528	0.219	211,600	107.219
250*	0.575	0.260	250,000	170.000
300*	0.630	0.312	300,000	210.000

*All sizes are AWG, except for the last two, which are in kcmils.
** For copper only, no insulation, single conductor through #8 AWG, then stranded for larger conductors.

The use of untested, unmarked conductors or conductors marked for other applications is, at best, a violation of the requirements of the *NEC.* At worst, it can create safety hazards that may result in property damage or loss of life.

Conductor Temperature Ratings

Conductors that are commonly available for use in PV systems were discussed in this column in *HP76 & 77.* These conductors come with insulation temperature ratings of 60°C (140°F), 75°C (167°F), and 90°C (194°F). These ratings determine the maximum temperature that the conductor insulation is allowed to reach. Insulation is heated from the heating of the copper conductor by current flowing in it, and from the temperature of the surrounding media (air, conduit, earth, etc). The presence of other nearby conductors also affects the temperature of a particular conductor.

Ampacity

The basic ampacities of conductors are listed in numerous tables in the *NEC.* Conductors in free air are addressed by Table 310-17. Conductors in conduit are covered in Table 310-16. The basic ampacity tables present the current ratings as a function of conductor size and insulation temperature rating at an ambient temperature of 30°C (86°F). The basic ampacities (at 30°C (86°F) and unmodified by temperature or other considerations) require that there are no more than three current-carrying conductors grouped together or installed in a conduit.

From this starting point, there are a number of rules that must be applied to determine how this initial ampacity is modified to determine the ampacity of the conductor in a particular installation. I encourage you to obtain a copy of the *NEC* to ensure that all conditions are met for determining the ampacity of a specific conductor in a specific application. The many rules are too numerous and too detailed to cover here, but I'll mention a few of the more commonly used ones:

- Ambient temperatures above 30°C (86°F) decrease the basic ampacity; temperatures below 30°C increase the ampacity.
- More than three current-carrying conductors grouped together (bundled or in a multiconductor cable) or installed in a conduit reduce the ampacity.
- Conductors operating in more than one ambient temperature have special requirements.
- #14, 12, and 10 (2.1, 3.3, and 2.6 mm^2) conductors have additional restrictions on maximum ampacity.
- Some installation methods (such as aerial feeders or tray cable) require special calculations.
- The temperature ratings of terminals, fuses, and circuit breakers connected to conductors may reduce the ampacity.

An Example of Code Complexity

Here is an example of what might be involved in determining the ampacity of the PV array output conductors on a residential system. Exposed, single-conductor #10 (2.6 mm^2) USE-2/RHW-2 is run from the modules to a combiner box. The conductor then runs in conduit (four conductors in the conduit for two circuits) through an attic, and down through the house to a basement power center.

The combiner box (in an ambient temperature of 40°C; 104°F) has fuses in it, and the power center has a circuit breaker (both have terminals rated for 75°C; 167°F). The basement is always a cool 22°C (72°F), the attic reaches 50°C (122°F), and the module junction boxes and backs of the modules are at 70°C (158°F). The outside temperature is 40°C (104°F). More than 10 percent of the exposed single-conductor cable from the modules is routed along the backs of the PV modules.

The temperature rating of 75°C (167°F) for the fuse and circuit breaker terminals limits how hot the conductor can be at those connections (Section 110-14(c)). The insulation temperature cannot exceed 75°C from a combination of the current flowing in the conductor and the ambient temperature at the location of each terminal or device.

This might indicate that we could use a conductor with a 75°C insulation to save a few pennies. However, this same conductor must operate near the backs of the modules and in the module junction boxes where the ambient temperatures are 70°C (158°F). The 75°C conductor temperature limitations for ambient temperatures this high dictate that the 90°C (194°F) cable specified (USE-2/RHW-2) be used and that 75°C rated cables would be inappropriate.

If we start in the basement, the basic 30°C (86°F) ampacity of this cable (#10 (2.6 mm^2) USE-2/RHW-2) is 40 amps (*NEC* Table 310-16). It is then increased by a factor of 1.04 because of the 22°C (72°F) ambient temperature (Table 310-16), and is decreased by a factor of 0.8 because there are four conductors in the conduit (Section 310-15(b)(2)(a)). This gives a modified ampacity of 33 amps (40 x 1.04 x 0.8 = 33 A). However, there is a note to the ampacity tables (see Section 240-3) that states that #10 conductors may not be used with overcurrent devices at more than 30 amps, which further restricts the maximum current we can run through the conductor.

When the ambient temperature is 30°C (86°F), a #10 (2.6 mm^2) conductor with a 75°C (167°F) rated insulation can handle 35 amps and stay below 75°C (Table 310-16). This comparison allows us to evaluate the temperature of the USE-2/RHW-2 90°C (194°F) conductor as it is connected to the circuit breaker terminal that is rated for a maximum temperature of 75°C. The circuit breaker terminal temperature is not exceeded because we keep the current below 35 amps due to the 30 amp limit on #10 conductors mentioned above.

In the hot attic (50°C; 122°F), we derate the conductors for temperature by a factor of 0.82 (Table 310-16) and for four conductors in conduit by a factor of 0.8 (Section 310-15(b)(2)(a)). The derated ampacity becomes 26 amps (40 x 0.82 x 0.8 = 26 A).

For conduit outside the house (preferably shaded) where the ambient temperature is 40°C (104°F), the derating factors result in an ampacity of 29 amps (40 x 0.91 x 0.8 = 29 A).

The single-conductor, exposed cables from the combiner box to the modules operate in a temperature of 70°C (158°F) as they are routed along the backs of the PV modules and into the module junction boxes. Because they are exposed (in free air), the basic 30°C (86°F) ampacity is 55 amps and the temperature derating factor is 0.41, yielding an ampacity of 23 amps (55 x 0.41 = 23 A) (Table 310-17). However, if they were grouped together in a set of four after coming out of the junction box, an additional factor of 0.8 should be applied, reducing the ampacity to 18 amps (Section 310-15(b)(2)(a)).

The temperature in the combiner box (in the shade) will be 40°C (104°F), which is the same as the ambient temperature. Again we have to evaluate the 75°C (167°F) rated terminals on the fuse. In this case, the ambient temperature is above 30°C (86°F), and the higher temperature contributes to the heating of the terminal. If the circuit currents are kept below 31 amps (35 x 0.88 = 31 A), the terminals will stay below 75°C (167°F) (Table 310-16).

First we have to determine the minimum size of the conductors based on the *NEC* requirements for ampacity. Then we should look at voltage drop, which is not an *NEC* requirement, although it is mentioned in the *NEC* as a suggestion. Voltage drop is a subject all by itself, and there are many opinions on how the calculations should be done.

Summary

Confusing, isn't it? We made ampacity calculations on this run of #10 (2.6 mm^2) USE-2/RHW-2 that resulted in ampacities of 33 amps, 30 amps, 31 amps, 29 amps, 26 amps, 23 amps, and 18 amps. The *NEC* requires that the lowest figure be used. In this case, that would be 18 amps or 23 amps, depending on how the exposed conductors were routed. In installing PV systems, the difficulty of these calculations is not great. However, finding all of the applicable requirements takes time and familiarity with the code.

There are additional requirements that might apply to a particular PV installation. A team consisting of a PV-familiar person (PV vendor/designer) and a code-familiar individual (electrician) makes for safe, reliable, and durable PV installations. In the next *Code Corner,* we will work the ampacity problem from the other direction, and address the circuit currents and how they are determined.

Questions or Comments?

If you have questions about the *NEC* or the implementation of PV systems following the requirements of the *NEC,* feel free to call, fax, email, or write me at the location below. Sandia National Laboratories sponsors my activities in this area as a support function to the PV Industry. This work was supported by the United States Department of Energy under Contract DE-AC04-94AL8500. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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